Investigating Alternative Extraction Methods at the MedAustron Ion Therapy Center

F. Kühteubl, L. Adler, P. A. Arrutia Sota, L. Fischl, M. A. Fraser, X. German, G. Guidoboni, K. Holzfeind, C. Kurfürst, C. Maderböck, M. T. F. Pivi, F. Plassard, D. A. Prokopovich, E. Renner, V. Rizzoglio, I. Strasik, C. Schmitzer, A. Wastl

Slow Extraction at MedAustron

MedAustron is a PIMMS-based facility which employs third-order resonant extraction with a betatron core [1]. Throughout the acceleration process, the beam is maintained off-momentum. A dedicated resonant sextupole is used to excite a third-order resonance at a horizontal tune of $Q_x = 5/3$. The beam is slowly extracted via acceleration in energy with the betatron core into resonance. As the beam approaches the resonance, the transverse amplitude of the particles within the unstable region increases every third turn. Particles that have a sufficiently large horizontal displacement enter an electrostatic septum which deflects the particles into the extraction channel [2, 3].

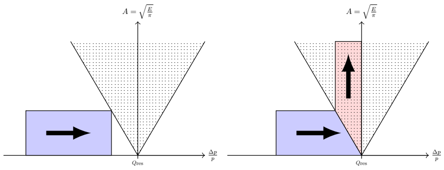


Fig. 1: Steinbach diagram for betatron core extraction

Alternative Extraction Methods

Radio Frequency Knock Out (RFKO)

With Radio-Frequency Knockout (RFKO), the amplitude of the circulating particles is gradually increased by applying a horizontal kick on the particles via a horizontal RF electric field application. To identify the optimal parameters for RFKO, a multidimensional scan was simulated for horizontal beam parameters. Simulation of the extraction process was performed with MAD-X [4] with evaluation of the extraction efficiency and distribution parameters of the extracted beam at the electrostatic septum (ESE).

Setup:

The excitation signal is generated using a Ettus USRP X310 Software Defined Radio (SDR). The revolution frequency, horizontal tune, and excitation pattern parameters are input to a GNU Radio script, which computes and produces the required excitation waveform. This output is fed through a 1 kW amplifier before connection to the Schottky plates via an RF BalUn. An RF switch, toggled via the control system, is between the SDR and the amplifier for extraction control.

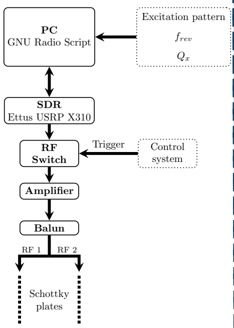


Fig. 2: RFKO setup at MedAustron.

Measurements:

Using the aforementioned setup, the beam could be extracted with a high efficiency of up to 95% and transmitted to the treatment room with a nearly constant particle flux. The use of the SDR in generating the RF excitation signal has allowed for a wide variety of signals to be evaluated with minimal effort.

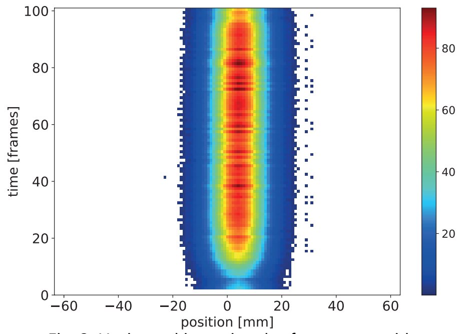


Fig. 3: Horizontal intensity plot for protons with 252.7 MeV at isocenter for RFKO extraction.

Constant Optics Slow Extraction (COSE)

Constant Optics Slow Extraction (COSE) is an extraction technique that involves the synchronous ramping of all synchrotron magnets to move the resonance into the stationary beam [5].

COSE is compatible with bunched beam operation, allowing the magnets to be ramped while the beam is still kept bunched. However, in bunched COSE, it is crucial to synchronously decrease the mean radial position of the beam relative to the resonance in synchronisation with the magnet ramping.

Multi Energy Extraction:

In bunched COSE, the energy of the beam can be altered during the spill, allowing for Multi Energy Extraction (MEE). For MEE, multiple COSE ramps are executed consecutively, separated by segments where no extraction takes place. During these non-extraction segments, the dipole strengths are adjusted while the feedback loops are active, forcing a relative change in beam energy. By moving the beam away from the resonance during the energy change, the likelihood of particles being extracted due to ripples from the power supply of the synchrotron magnets is minimised.

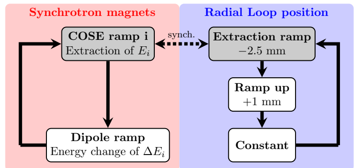


Fig. 4: MEE with bunched COSE at MedAustron.

Measurements:

Fig. 5 presents the extraction of ten energies, each with an energy difference ΔE_i of 300 keV, utilising bunched COSE. The upper plot displays the measured mean radial position of the beam, while the lower plot shows the extracted intensity. The extraction phases are highlighted in grey, while the energy change phases are depicted in white.

During the energy change phases, the extraction is almost completely suppressed. To homogenise the intensity of the sub-spills, the respective COSE ramp rates can be adjusted accordingly.

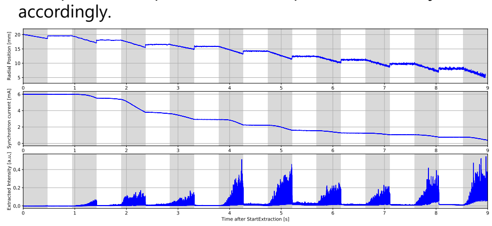
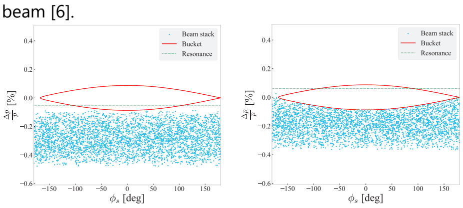


Fig. 5: 10 energies MEE with bunched COSE.

Phase Displacement Extraction (PDE)

Phase Displacement Extraction (PDE) involves sweeping an empty bucket through the beam stack by altering the frequency offset of the cavity. The bucket configuration is set up to overlap with both the resonance and the waiting beam, so that the particles that are following the separatrix are accelerated into resonance as the bucket traverses the beam [6].



a) t = 0 b) $t = t_{sweep}$

Fig. 6: Longitudinal phase space for PDE at the start and the end of the bucket sweep.

The speed of the sweep can be controlled by adjusting the ramp rate of the frequency offset. Multiple sweeps can also be combined for pulsed extraction. In this case, when the frequency is ramped back to the starting point, we set the bucket voltage (and hence the bucket height) to zero to prevent any extraction. Once back at the starting point, the voltage is increased again, and the sweep can be repeated.

Measurements:

PDE was successfully tested at MedAustron, demonstrating the capability of the RF system of the synchrotron to perform multiple bucket sweeps. However, further refinements are necessary regarding the frequency sweeps and bucket voltage to ensure a constant intensity and effective extraction.

Figure 7 shows PDE for protons with 252.7 MeV with two frequency sweeps from 3 kHz to 0 kHz with a bucket voltage of 1 kV. The upper plot depicts the frequency offset, while the middle plot shows the bucket voltage. The lower plot displays the extracted intensity. As almost all particles are already extracted during the first sweep, the extracted intensity for the second sweep is much lower.

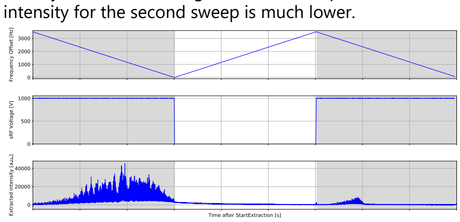


Fig. 7: PDE with two frequency sweeps for protons with 252.7 MeV

Conclusion

Successful testing of alternative extraction methods, namely Radio-Frequency Knockout (RFKO), Constant Optics Slow Extraction (COSE), and Phase Displacement Extraction (PDE), was carried out at MedAustron. The proof of concept was demonstrated for each method by extracting the circulating beam into the treatment room. However, further optimisation is required to establish these techniques as viable alternatives to the default betatron core extraction method at MedAustron.

Table 1 provides a summary of the advantages and disadvantages of each tested technique for possible clinical usage. RFKO and COSE are both compatible with bunched beams, making them suitable for MEE. On the other hand, PDE requires an empty bucket and is thus not compatible with bunched beams for the current setup at MedAustron. All three techniques could achieve extraction rates compatible with FLASH, however RFKO and COSE may require some technical adaptation for faster extraction rate implementation.

Tab. 1: Summary of alternative extraction methods

	Extraction method		
	RFKO	COSE	PDE
Bunched beam	✓	✓	✗
MEE	✓	✓	✗
FLASH	(✓)	(✓)	✓

References

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florian.kuehteubl@medaustron.at